[Proc. Roy. Soc. Victoria, 29 (N.S.), Part I., 1916].

Art. III.—*The Petrology of the Silurian Sediments near Melbourne.*

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(Communicated by Professor E. W. Skeats, D.Sc.)

1.—Introduction.

Silurian sediments form the base rocks of the city of Melbourne. Typical outcrops are exposed along the River Yarra from Princes' Bridge upwards, in Hawthorn and Kew, and also in the northern and western suburbs, Coburg and Moonee Ponds. Carefully selected specimens were taken from most of the outcrops. The rocks are remarkably uniform in megascopic and microscopic characters over the whole of Melbourne, so that the comparatively small collection of specimens may be taken as representative.

The rocks consist entirely of shales, mudstones and sandstones, thinly bedded. The beds average one or two feet in thickness. The shales and mudstones are loosely compacted but in certain cases are firm and tough where silicified. The sandstones contain much aluminous material. In some cases they are partially cemented into semi-quartzites by secondary silicification. In most cases the cement consists of fine clayey material, in which case the rock weathers down to a soft, porous, crumbly sandstone. The quartzite beds stand out in prominent relief from these. There has been an extensive replacement of the sandstones by limonite along the bedding planes.

These sediments are steeply folded and fractured around Melbourne. In general the strike is northerly, but owing to the complications of movements, such as sagging and pitching of the folds, and to the presence of numerous fractures, the strikes vary greatly from that of the main fold axes.

Some fairly large faults occur. In the bed of the Merri Creek at Coburg (see "Description of Sections," Rock No. I.) there occurs a well-developed fault breccia composed of angular fragments of sandstone, resembling the neighbouring Silurian sandstones, set in a matrix of the same material, and now almost entirely replaced by limonite. Small displacements are very widespread.

2.—Composition of the Sediments.

The sandstones, mudstones and shales are all highly aluminous. The principal allothigenic minerals identified microscopically are quartz, more or less fresh felspars, muscovite, and biotite. The accessories noted are tourmaline, iron oxides (magnetite or ilmenite), zircon, rutile, and perhaps anatase and sphene. Secondary or authigenic minerals present are sericite, limonite, leucoxene, quartz, and possibly pyrite, subsequently altered to limonite. Carbonates may occur to a small extent but no effervescence with acid was observed with the powdered rocks. Chlorite after biotite is present in some sections.

(*a*). *Essential Minerals.*—The detrital quartz ranges to about 0.5 mm. as a maximum in the sandstones. In some of the sandstones small well developed quartz veins have been formed by secondary solution and redeposition.

The quartz is angular in habit. It does not show any crystal boundaries. It frequently shows strain polarisation effects as the result of pressure. Inclusions of such minerals as apatite are sometimes found.

The felspar is found in two conditions. The greater amount occurs as turbid grey patches throughout the section of about the same size as the quartz, and in some cases in nearly as large an amount. These patches show, in some cases, remains of lamellar twinning. They consist essentially, as far as can be determined, of fine aggregates of secondary sericite. The original felspars have probably been altered by percolating solutions producing secondary mica. In some cases these sericitic patches have been subsequently stained by limonite impregnations.

A few unaltered grains of oligoclase occur in most of the sections. The refractive index, twin lamellation, and such extinction as can be observed refer it to oligoclase. These again are of the same order of magnitude as the quartz.

No felspar has been identified in the mudstones and shales, though possibly originally present.

Mica occurs in three forms :—1, As long ragged clear crystals of muscovite sometimes nipped in between the neighbouring sand grains. These are clearly detrital and average about one millimetre in length. 2, As secondary sericite after felspar, and also throughout the groundmass constituting most of the clayey matter of the groundmass. This may be partly allothigenic and partly authigenic as is certainly the case with that representing felspar remains.

The above minerals are characteristic of every sandstone examined.

3, As biotite. This occurs in several of the sandstones. It is generally pleochroic from a pale greenish yellow to a darker tint. In some sections it is nearly as plentiful as the muscovite. It has the same relative size. The colour may be partly due to iron-staining. In some cases it has been altered to chlorite.

(*b*). *Accessory Minerals.*—Tourmaline is the chief accessory. It is to be found in every sandstone sectioned. It was not identified in the shales or mudstones. It occurs as rounded detrital grains showing marked pleochroism from greenish-brown to colourless. It sometimes shows good crystal boundaries.

Zircon occurs in most of the sections. It is generally in more or less rounded grains showing the remains of crystal faces. It is always clear and colourless.

Rutile occurs in rounded detrital grains. These are mostly dark reddish brown, but in one case a dark grey grain was identified.

Black Iron ores occur throughout the rocks in irregular grains, either as magnetite or ilmenite.

A certain amount of carbonaceous material may occur in some of the rocks, but cannot be differentiated from the iron oxides.

Anatase and sphene possibly occur, but their identification was not definite, owing to the very small size of the grains.

(*c*). *Secondary Minerals.*—Limonite is the chief secondary mineral. It replaces quartz and mica and probably also felspars. It is responsible for the general colour of the sandstones. It is not so prominent in the shales. Pale-green chlorite occurs as an alteration product of the biotite. Secondary quartz veins are present in some of the sandstones. Secondary rutile occurs as fine needles in sericitic matter, possibly after biotite.

Separation of Minerals with Heavy Liquid.

A heavy liquid separation was undertaken to isolate other minerals which might be represented in small quantity. A promising sandstone No. 13 (see " Description of Sections ") from Studley Park was crushed in a mortar and passed through a 120 mesh sieve and then the fine muddy material was panned off with water. This method of separating the fine material saved any small particles of heavy minerals which might be present, but got rid of the fine quartz and micas.

The washed product was then divided into two portions by an electromagnet. The demagnetised product was then again separated into two portions, a heavier and a lighter by means of flotation in acetylene tetrabromide S.G. 2.938, following the general method described by T. Crook, A.R.C.Sc. (Dublin), F.G.S., in Hatch's "Petrology of the Sedimentary Rocks."

The heavy portion was then examined under the microscope in media of different refractive indices. The following minerals were thus recognised :—Tourmaline, zircon, rutile, magnetite, sapphire, topaz, a little biotite and chlorite, some quartz, probably attached to some of the other minerals during flotation, and perhaps kyanite.

The tourmaline is abundant, and in many cases shows good crystal boundaries. It contains many microscopic inclusions of other minerals, and of gas bubbles. It is generally yellow brown to dark brown, but some fragments polarise from a blue green to a pure green.

Zircon comes next in abundance. The crystals show almost perfect crystal faces and are in many cases zoned. Faces shown include prisms and pyramids.

Rutile occurs as dark brown prisms generally, with pinacoidal terminations.

Magnetite was also noticed in the demagnetised (?) product. It shows characteristic rectangular outlines. It was probably too small in this case to separate itself efficiently from the sand under magnetic influence.

Sapphire occurs as deep blue, slightly pleochroic, irregular, angular grains, showing low polarisation colours, and is fairly plentiful.

Topaz occurs as rounded and irregular grains, and in many cases has many inclusions, some dark, which are probably iron ores.

A little biotite altering to chlorite was found. In one case the chlorite showed a fine spherulitic structure.

A doubtful crystal of kyanite was recognised, but as only one grain was found it is not considered wise to positively assert its presence.

3.—Description of Rock Sections.

Note.—The rock sections are included in the collection of the Geological Department of the University.

(*a*). *Coburg Specimens.*—Rock No. 1 consists of a hard breccia composed of angular sandstone fragments set in a matrix of finer material largely replaced by iron oxides.

Microscopically the rock fragments show quartz, muscovite, and tourmaline set in a groundmass of quartz and secondary mica. The rock is clearly a fault breccia. It is to be found about 100 yards east of the Newlands Street West bridge over the Merri Creek in the creek bed.

No. 2 is a typical micaceous sandstone. It is a yellowish loosely compacted rock showing quartz grains and flakes of muscovite. Microscopically it shows quartz, muscovite and tourmaline. This specimen was obtained from the road section just west of the cemetery in Elizabeth Street.

No. 4a is a light yellow mudstone. Microscopically all that can be recognised are minute fragments of quartz and muscovite set in a micaceous clayey groundmass. Spots of reddish-brown mineral with cubical outlines are possibly limonite after pyrite. It was obtained just to the west of the Newlands Street West bridge over the Merri Creek.

(*b*). *Moonee Ponds Creek Specimens.*—No. 3 is a dark, fine-grained sandstone, splitting well along the bedding planes. The split faces are covered with small flakes of muscovite. The rock shows dark bands. Microscopically the section shows quartz, muscovite, biotite, altered plagioclase, oligoclase (fresh), zircon, tourmaline, rutile, and ilmenite or magnetite, and dark bands of carbonaceous material. Some of the quartz grains contain inclusions of apatite. The tourmaline shows good crystal faces in some cases. Secondary minerals present are sericite, chlorite after biotite, a little carbonate, and limonite. The specimen was obtained from a cliff section on the creek about 100 yards north of the Brunswick Road bridge.

(*c*). *Hawthorn Specimens.*—No. 5 was obtained from a small point on the left bank of the River Yarra, just below the bend up stream from the Glen Tea Gardens. It is a dense grey sandstone, showing quartz and muscovite. Deposition of limonite has taken place along joint planes.

The section shows quartz, muscovite, tourmaline, zircon, fresh oligoclase and altered plagioclase, magnetite or ilmenite, leucoxene and green biotite, also possibly sphene. Some carbonaceous matter is present. Secondary limonite and sericite and clayey interstitial matter are also present.

(*d*). *Kew Specimens.*—i., Victoria Street Bridge Section—Rock No. 17 from the north side of Victoria Street at the top of the hill above the bridge is a fine grey sandstone traversed by veins of limonite and secondary quartz. Microscopically the section shows quartz, muscovite, tourmaline, zircon, and carbonaceous material, set in a fine groundmass of quartz and sericite. Sericite after felspar is common. The secondary quartz veins are probably later than the limonite impregnations, as they cut through them in places. The quartz veins crossing small cracks may have offered an obstruction to subsequent iron-bearing solutions.

No. 19 is a light-grey micaceous sandstone showing quartz, muscovite, tourmaline, zircon, biotite, and oligoclase in a fine groundmass of quartz and sericite. Secondary minerals present are limonite, sericite, and chlorite. This rock was obtained about two chains below No. 17 on the north side of the cutting.

No. 20 is a yellowish loosely compacted micaceous sandstone similar to No. 2 from Coburg. It was obtained about half a chain below No. 19. It shows quartz, muscovite, tourmaline, oligoclase, altered plagioclase, biotite, zircon, rutile, chalcedony fragments, and possibly anatase. Secondary minerals are limonite, leucoxene after ilmenite, sericite, and chlorite.

No. 22 is a hard, porous, greyish-white quartzite, showing flakes of muscovite. Microscopically it shows quartz, muscovite, tourmaline, altered plagioclase, magnetite or ilmenite, zircon, leucoxene after ilmenite, and rutile in a groundmass of fine quartz and sericite. Secondary rutile occurs in very fine needles in cloudy sericitic patches, possibly altered biotite. It was obtained from a prominent bed six chains from No. 17 on the same side.

ii., Studley Park Specimens.—No. 6 is a hard, compact sandstone traversed by secondary quartz and limonite veins. The section shows quartz—some with apatite inclusions—a very little muscovite, zircon, rutile, tourmaline, magnetite or ilmenite, sphene, and secondary sericite and limonite. The location of all Studley Park specimens is shown on the sketch map (see below).

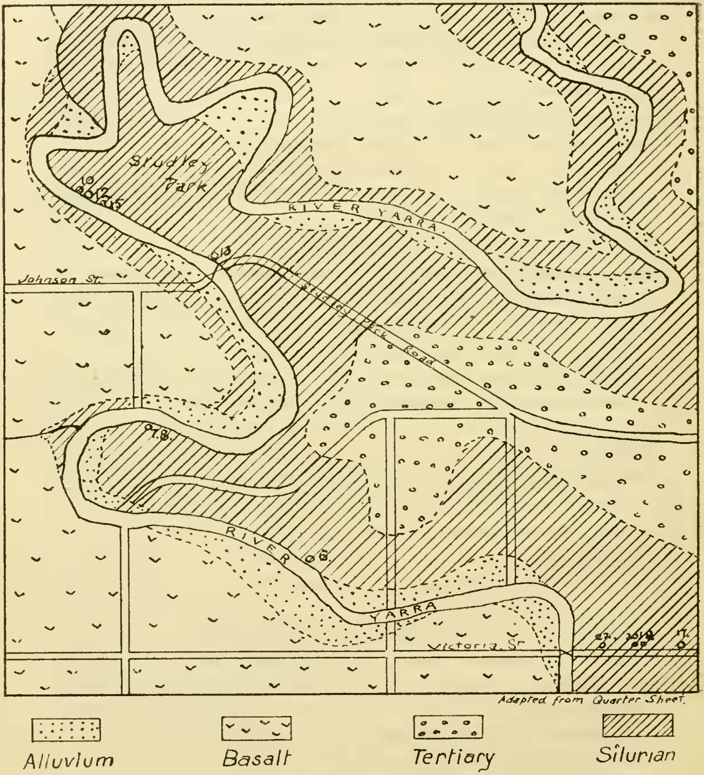
No. 8 is a micaceous mudstone with grey and yellowish bands. Microscopically it shows distinct current bedding. Minerals identified in the section include quartz, muscovite, and tourmaline, with secondary sericite and limonite. Some of the limonite is probably secondary after pyrite judging by its crystal outline.

No. 10 is a white mudstone from the crest of an anticline on the river path, about a quarter of a mile N.W. of Johnston Street Bridge. Microscopically it shows quartz, muscovite, biotite, chlorite, sericite, and limonite. It is fairly even grained, with a few larger fragments of quartz here and there.

No. 12 is a yellowish, hard, dense quartzite with secondary quartz and limonite veins. Microscopically it shows quartz, muscovite, oligoclase, altered plagioclase, tourmaline—brown and grey—zircon, cherty and sericitic interstitial matter, chlorite and limonite.

No. 13 is the rock selected for separation by heavy liquid. Microscopically the following minerals were identified:—Quartz, muscovite, tourmaline, oligoclase, altered plagioclase, magnetite, zircon, rutile, biotite, and secondary sericite and limonite.

No. 15 is a banded grey and yellow shale showing muscovite along the bedding planes. Under the microscope the section shows quartz,



GEOLOGICAL MAP of KEW

0 ½ 1 mile.

muscovite, and carbonaceous material in a clayey groundmass. It is very even grained.

(*e*). *South Yarra Specimen.*—No. 9 was obtained from the cliff section on the left bank of the River Yarra just below the Church Street Bridge. It is a hard, tough, cherty looking rock. Under the microscope it shows small angular fragments of quartz, and a little muscovite, tourmaline, and rutile, in a very fine sericitic groundmass. It seems to have suffered considerable pressure. Secondary limonite is also present throughout the rock.

4.—Metamorphism.

Practically no metamorphism of the rocks has occurred. Although intensely folded and fractured no cleavage is developed. No contact metamorphism has taken place.

The series is intruded by two series of dykes, one basaltic and the other of the nature of quartz porphyry. The only alteration is that due to the percolation of solutions containing iron derived from the dykes. The sediments are largely impregnated with limonite at the contacts.

5.—Deposition of the Sediments.

Chapman[1] refers the Melbournian sediments to a warm shallow sea on the evidence of the prevalence of the brachiopod Lingula, and the almost complete absence of the corals. This view is supported by the writer. The general fineness in grain suggests that the sediments were deposited some distance from the shore. Conglomerates occurring at Keilor, about 10 miles from Melbourne, probably represent the nearest part of the shore line sediments of the Silurian sea.

The admixture of relatively coarse sand with the fine materials of the shales suggests that the sediments may have been laid down under flood conditions or under rapid variations in the strength of the currents. This view is supported by the relative thinness of the beds and the rapid alternation of sandstone and shale.

6.—Origin of the Constituent Minerals.

Two sources are possible for the material of the sediments :—

i. They may have been derived from a pre-Silurian igneous rock ; or, ii., They may have been derived from a pre-Silurian sediment. Both sources are also possible.

1. "On the Palaeontology of the Silurian of Victoria." Proceedings of Section C, p. 213, Australasian Association for the Advancement of Science, Melbourne, 1913.

Jutson[1] believed that the Silurian sediments at Warrandyte were derived solely from a sedimentary series because no pebbles of igneous rock were found by him in the Warrandyte conglomerate.

Junner,[2] in his paper on the Diamond Creek area, concludes that the sandstones of that district were derived to a "fair extent" from pre-Silurian igneous rocks. He gives the following reasons for his view :—

1. The abundance of muscovite.
2. The presence of biotite, plagioclase, and chlorite, which is usually derived from unstable iron magnesium minerals.
3. The occurrence of zircon and rutile crystals in the quartz grains in the sandstones may indicate an igneous origin for such quartz.
4. The constant presence of tourmaline suggests such an origin.
5. The absence of metamorphic minerals, etc., shows that they were not derived from metamorphic rocks.

The last does not show, however, whether the Silurian sediments were derived from igneous or sedimentary rocks. Muscovite and tourmaline, whilst suggesting an originally igneous origin, are stable minerals and may easily be handed down from one sediment to another. Similarly, quartz grains containing zircon and rutile may easily have suffered more than one transportation before coming to their final resting place.

The presence of biotite, plagioclase and chlorite suggests that the rocks were derived to some extent direct from pre-Silurian igneous rocks, especially if the felspar were fairly fresh.

The writer finds felspar to be present in two conditions in his sections; the one much decomposed but showing traces of twin lamellation, and the other quite clear and fresh. The natural inference from this fact is that the decomposed material has suffered more handling than the fresh. This would suggest that the clear material has been directly derived from an igneous source, possibly granitic, whilst the decomposed material has been derived from an older sediment. No pre-Silurian granites, however, are known near Melbourne with certainty. The You-Yangs granite may be pre-Silurian.

The writer inclines to the view that both origins are probable for the rocks of the Melbourne district. This view is strongly supported

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1. "The Structure and General Geology of the Warrandyte Gold-field, &c." Proc. Roy. Soc. Victoria, vol. xxii., pt. II., 1911.

2. "General and Mining Geology of the Diamond Creek Area." Proc. Roy. Soc. Victoria, vol. xxv., pt. II., 1913.

by the fact that the plagioclase occurs in two conditions. The presence of biotite and chlorite supports the view of an igneous origin for part of the sediments.

The strain polarisation of some of the quartz may have been produced, not in situ but in an older sediment. Our known Ordovician rocks have suffered much greater stresses than the Silurian. All the quartz does not show strain polarisation.

The Ordovician sediments of Victoria have not yet received any attention petrologically. When they are examined they will probably show the presence of much similar material to that of the Silurian. An Ordovician quartzite section in the writer's possession shows zircon and tourmaline.

In conclusion the writer wishes to gratefully acknowledge the invaluable help and guidance of Professor Skeats through all stages of the work, and to Dr. Summers for various suggestions.